WORKS OF

PROF. HENRY FAY

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MICROSCOPIC EXAMINATION OF STEEL

BY

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PREFACE.

The material contained in this small volume was originally issued by the Ordnance Department U. S. A. and represented the results of investigative work carried on at the Watertown Arsenal. It was intended for the exclusive use of inspectors of ordnance material. The demand for the pamphlet however was considerable, and it was thought that it might serve a wider field of usefulness by being offered to others interested in the inspection of steel. It is in no sense to be considered a text book, and it is meant to present a mere outline of metallographic methods illustrating typical examples, and should be used only in conjunction with a study of text books on the metallography of iron and steel and with reference to original papers appearing in the journals bearing on this subject. It should, furthermore, be used with caution, as it is believed that metallographic diagnosis can be made only after much experience in the handling of a variety of material. This volume is intended particularly for those who are in need of some help in the interpretation of results.

The author wishes to express his appreciation of the kindly interest which Colonel Wheeler, the Commandant of the Watertown Arsenal, has shown in this as well as in other work of similar nature.

HENRY FAY.

CAMBRIDGE, MASS.
November, 1916.

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It has been considered advisable to make these books manuals of practice, rather than theoretical discussions of the subjects treated. The theory is fully discussed in text books, hence the engineer who has previously mastered it there, is, as a rule, more interested in the practice. The Wiley Engineering Series therefore will present the most approved practice, with only such theoretical discussion as may be necessary to elucidate such practice.

Microscopic Examination of Steel

INTRODUCTION.

The supreme test of any metal is a test to destruction, but unfortunately this method is usually too expensive and time consuming to lend itself to useful purposes. A practical field test is also satisfactory, but in order to carry on such a test in a systematic manner a certain amount of information must be obtained previous to the assembling of the materials for such a test. In order to judge whether or not a metal is suitable for the purpose for which it is intended separate parts of the metal are selected for test and upon the results of these tests the metal is judged as a whole. Physical and chemical tests are usually applied and both give satisfactory and necessary information within certain limits but neither is absolutely conclusive in itself and the results of the two methods of testing should always be used in conjunction.

To further supplement the information obtained by physical and chemical tests metallographic tests which give information not obtainable by the other methods have been introduced. The particular use of metallographic testing is to give information in regard to the homogeneity of the metal, and the heat treatment to which it has been subjected. These observations are extremely useful in conjunction with the results of the other methods, but are not sufficient in themselves at the present time as a basis for conclusion, on account of not yet having been sufficiently standardized. Interpretation of results is an important factor, and in cases of doubt the results should be referred to someone having had experience.

The following pages are submitted as a help to inspectors, who should inform themselves more fully in regard to underlying principles involved and to methods employed.

SLOWLY COOLED STEELS.

When steel passes from the liquid to the solid state it fo
what is called a solid solution. This solid solution is usu
referred to as Austenite. The temperature at which the cha
from liquid to solid metal takes place is progressively lowe
with increase of carbon. The resulting solid solution is s
ject to certain reactions which take place as the solid mas
further cooled. The temperatures at which these reactions t
place are known as critical temperatures, or critical points,
are made evident by evolutions or absorptions of heat.
reactions are reversible ones, depending upon whether the poi
are observed on a rising or falling temperature. Points
tained upon a falling temperature are referred to as Ar_3,
Ar_1; points obtained on a rising temperature as Ac_1, Ac_2,
Ac_3.

The reactions which take place at these critical temperatu
determine the character of the resulting product. Inasmuch
some of these points are dependent upon the percentage com
sition of the metal, particularly carbon, the properties of
steel are then dependent upon the percentage of carbon and
completeness with which the reactions have taken place at
critical temperatures.

For practical purposes, the Ar_2 and Ac_2 points need not be c
sidered. In steels containing less than 0.85 per cent carbon,
Ar_3 point represents the beginning of the decomposition of s
solution and the throwing out of some of the solvent, viz., ir
The temperature at which this reaction begins is progressiv
lowered with increase of carbon up to 0.85 per cent. In ste
containing more than 0.85 per cent carbon the upper critical te
perature is progressively raised with increase of carbon up
1.7 per cent carbon and is referred to as A_{cm}, and the react
taking place represents the beginning of the separation of i
carbide (Fe_3C) on a falling temperature, and the completion
solution of iron carbide on a rising temperature. The Ar_1 po
for all carbon steels is approximately at the same temperature a
represents the final decomposition of the solid solution into

constituents, iron and iron carbide. The Ac_1 point is approximately 30° higher than the Ar_1 point, and represents the beginning of the formation of solid solution. In steels containing 0.85 per cent carbon there is but one critical temperature at which the solid solution decomposes into its constituents, iron and iron carbide. This is known as an eutectoid steel, and its microscopic constituent is pearlite. Pearlite always etches dark, and under high magnifications is shown to consist of alternate laminations of iron and iron carbide. Steels containing less than 0.85 per cent carbon are hypoeutectoid, and contain the microscopic constituents ferrite and pearlite, the amount of the latter increasing with the per cent of carbon. Steels containing more than 0.85 per cent carbon are hypereutectoid, and contain the microscopic constituents cementite (iron carbide, Fe_3C) and pearlite. These facts are illustrated in the diagram. (Fig. 1.)

Hypoeutectoid steels are used for forgings and castings; hypereutectoid steels for tools; eutectoid steels for tires, springs, etc. Examples illustrating these constituents are shown in photographs Nos. 1–9.

Photograph No. 1 shows the characteristics of a carbonless iron in which the whole field is made up of granules of ferrite. With the introduction of carbon there is a decrease in the amount of ferrite and the constituent pearlite begins to appear. This is shown in photograph No. 2 for a steel containing 0.18 per cent carbon. Inasmuch as steels containing 0.85 per cent carbon contain 100 per cent pearlite, and as pearlite is composed of ferrite and cementite, in this steel containing 0.18 per cent carbon there ought to be approximately 20 per cent of the field made up of pearlite. In a steel containing 0.5 per cent carbon there should be 58.8 per cent pearlite. Such a steel is shown in photograph No. 4. A eutectoid steel containing 0.83 per cent carbon and practically 100 per cent pearlite is shown in photograph No. 7. Under higher magnifications pearlite shows the laminated structure shown in photograph No. 8. In hypereutectoid steels the excess carbon beyond that necessary to form pearlite, separates as free cementite and the amount of free cementite can be calculated. Inasmuch as the whole field is made up of pearlite

and cementite and it requires 0.85 per cent of the carbon to form the pearlite, the difference between the total carbon and 0.85 per cent carbon gives the amount of carbon available to form cementite. Thus in a steel containing 1.25 per cent carbon there is available for cementite formation 0.4 per cent carbon and as cementite, Fe_3C, contains 6.67 per cent carbon the 0.4 per cent carbon would furnish approximately 6 per cent cementite which would occur in the free state, and the steel would contain 94 per cent of pearlite and 6 per cent cementite. See photograph No. 9. It is thus evident that by microscopic examination a rough determination of carbon may be made on *slowly* cooled steels. Photograph No. 10 shows a steel containing 1.46 per cent carbon — approximately 9 per cent cementite — in which the white constituent is cementite.

RAPIDLY COOLED STEELS.

Every chemical reaction has a time factor. In the slow cooling or heating of steels the reactions taking place at the critical temperatures are almost complete and the products of the reactions are in a state of stable equilibrium. If this time factor be disturbed, the state of equilibrium is also disturbed. If the rate of cooling is rapid enough, the reactions which ordinarily take place on slow cooling are suppressed and the metal is maintained in the condition in which it existed at the temperatures from which cooling began. If cooled rapidly from above Ar_1, the reactions which ordinarily take place on slow cooling have not time to take place and the solid solution present persists at the ordinary temperatures, but inasmuch as solid solution of iron carbide in iron is in stable equilibrium only at temperatures above Ac_1, then it must be in a state of unstable equilibrium at the ordinary temperature. This is the condition of hardened steel and is produced by quenching in water, brine, or oil at some temperature above Ac_1. The tendency toward stable equilibrium is very small at the ordinary temperature, but it increases with rise of temperature and time. The microscopic constituent produced in quenched steel is known as martensite and is characterized by needlelike crystals crossing each other at angles of 60°.

otograph No. 11 shows the characteristic appearance. Com-
rcially martensitic steels are unimportant on account of their
reme brittleness and they are found only rarely.

More important, however, are those steels in which the un-
ble state of equilibrium has been partially relieved by the
ocess known as tempering or drawing.

If heated to temperatures below Ac_1, the effect produced will
ry with the temperature. The lower the temperature of re-
ating the smaller is the tendency toward stable equilibrium;
e higher the temperature the more stable is the product pro-
ced. Practically any degree of hardness may be produced,
rying from glass-hard to extreme softness, by properly regu-
ing the temperature of the heating. There are then two
remes, the martensitic steels formed by quenching from above
1 and the pearlitic steels formed by cooling slowly from Ar_1 or
ove. Intermediate between these extremes are steels in which
re or less of the unstable solid solution has been partly con-
ted to more stable forms. Such forms are represented mi-
scopically by troostite and sorbite. Troostite, formed by
mpering at relatively low temperatures, represents the first
ge in the breaking down of the unstable equilibrium and is
aracterized by the amorphous or slightly granular structure.
etching with alcoholic nitric acid the surface usually blackens
mediately from separated carbon. Photograph No. 12 shows
ostite.

Sorbitic steels are those which have been quenched and heated
a higher temperature and thus represent a more stable state
equilibrium. They are characterized by having a peculiar
ayish color, and the structure is better defined than troostite.
e particles of iron carbide have not assumed definite lami-
tions with ferrite as in pearlite, but are very much more dis-
ct than in troostite. Photograph No. 13 shows sorbite.

Similar effects may be produced by varying the rate of cooling.
us, if the steel be quenched in the critical range at the be-
ning of the transformation of solid solution into its compo-
nts, troostite may be produced; if quenched near the end of
e transformation, sorbite may be produced. Quenching be-

low the critical range should theoretically produce the same effects as slow cooling.

ANNEALED STEELS.

In the heating of steels to a high temperature, and in the slow cooling from a high temperature either without having been forged or after having been forged at a high temperature, there is considerable grain growth of the steel with strong tendency toward granulation. In the making of castings there is good opportunity for grain growth and also for the formation of internal strains. To remove strains and to refine the grain, steel is annealed. The temperature of annealing is determined by the percentage of carbon. For hypoeutectoid steels the temperature most suitable is coincident with the temperature at which complete diffusion or solution of the constituents takes place. This corresponds to the Ac_3 point, and for steels containing less than 0.85 per cent carbon is progressively lowered from 900° C. for pure iron to 700° C. for eutectoid steel. Usually a temperature 25° to 50° higher should be reached.

In hypereutectoid steels the tendency for the structure to coarsen is very much greater, and consequently the heating for annealing should be carried only a little over the Ac_1 point.

Microscopic examination gives a clew not only to the temperature at which a steel has been annealed, but also gives a very strong indication of the rate at which cooling has taken place.

NON-METALLIC IMPURITIES.

In addition to the normal constituents of steel there are some abnormal constituents commonly classified under the name of slag, which may include such substances as silicate of manganese, sulphide of manganese, and oxide of iron. Mixtures of silicates of iron and manganese may occur and also mixtures of silicate of manganese and sulphide of manganese. Oxide of iron ordinarily occurs near the surface as the result of rolling in some mill scale, but may at times penetrate quite deeply into the interior, and in either case is usually accompanied by partial decarbonization.

It is difficult at times to distinguish readily between silicate and sulphide of manganese without resort to special tests. They both occur as dove-colored constituents and are best observed on the polished but unetched surface. See photographs Nos. 17 and 18. The former, especially if occurring in masses, will frequently show crystalline etch figures. See photographs Nos. 14 and 15. In slowly cooled, unworked steel they will show as rounded dove-colored masses usually in the ferrite; in forged steels they are elongated in the direction of forging. See photographs Nos. 16 and 17. Inasmuch as all steels contain some slag, it is a matter of opinion as to how much should be allowed. The form in which it occurs is of greater importance than the actual amount present, although the smaller the amount of slag the better the product. It is especially undesirable to have the slag in masses, and particularly in elongated streaks. It then produces ghost lines and is usually accompanied by streaks of ferrite which are usually further embrittled by the presence of high phosphorus. Such slag streaks are frequently the source of cracks which develop along the slag in the direction of forging.

By reference to photographs Nos. 14 to 18 may be seen some of the forms in which slag may occur, and other examples may be seen under the discussion of special cases.

Inspectors should observe the following:

(1) Macrostructure for (*a*) ingot structure, (*b*) segregation, and (*c*) blowholes.
(2) Slag.
(3) Streaks.
(4) Heat treatment.
(5) Composition.

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MACROSTRUCTURE.

Macrostructure is the appearance of the etched surface seen by the naked eye. Microstructure, on the other hand, is that appearance of the etched surface seen under a microscope. The macrostructure often yields important evidence concerning the qualities of the metal. The structure is usually developed on

a roughly polished area of considerable size, or if it is possible to work only with small sections, it is recommended that the test bars be rough-polished on two sides, at right angles to each other, before being turned into shape. The development of the structure is accomplished by etching the surface with a 6 per cent solution of iodine in alcohol or with an 8 per cent solution of copper ammonium chloride. The former should always be prepared immediately before use, as it keeps in good condition only a relatively short time. The copper ammonium chloride should be used only for those specimens which can be dipped into it, and the time of action should be approximately 1 minute. This solution will not give results with alloy steels on account of the tenacity with which the deposited copper adheres to the surface. With carbon steels the deposited copper is very easily removed by rubbing with a piece of wet cotton.

In using the iodine the polished surface is swabbed with cotton holding the reagent, and the process is repeated, as fast as the color of the iodine disappears, for a period of five minutes. The macrostructure thus developed shows ingot structure, segregation of carbon or phosphorus, excessive slag, strained metal.

The presence of ingot structure such as shown in photograph No. 19 indicates that the heat treatment and forging have not been sufficient to wipe out the crystallization which occurred on the solidification of the metal. It is not definitely known that the presence of ingot structure is harmful, and it is frequently accompanied by excellent microstructure, but it serves as an indication of the heat treatment to which the metal has been subjected after solidification. It is believed that such a structure would not be found in the best steel, and it is further believed that metal showing ingot structure would be more liable to rupture from shock than metal in which the ingot structure had been wiped out by heat treatment and forging.

Segregation of carbon or phosphorus may be brought out most successfully by etching a complete cross section of the metal under investigation, such as shown in photograph No. 20 of a rail section in which segregation of carbon is shown, or in photograph No. 21 of a cross section of a piece of cold-rolled shafting

in which segregation of phosphorus is shown. Photograph No. 22 shows a longitudinal section of the same piece of shafting and is etched with nitric acid, which darkens the phosphide areas. It is seldom possible, however, to obtain complete cross sections, but valuable indications may be obtained from surface structures or from test-bar sections, such as shown in photograph No. 38 of test bars marked 2, 3, and 5. The phenomena observed here will be more fully discussed later.

Both iodine and copper ammonium chloride show dark areas where segregated carbon occurs; iodine leaves phosphide areas whiter than the surrounding metal, while copper ammonium chloride leaves the area dark, and the copper adheres more tenaciously to a phosphide than to a carbide area. Excessive slag is shown by a pitted or spongy area where the slag has segregated.

Strained metal invariably etches more darkly than metal which has not been strained, and the extent of the strained area may be determined by etching with either reagent. Photograph No. 23 shows an area which has been strained by cold work.

SLAG.

Slag is undoubtedly harmful if the material, either silicate or sulphide, occurs in large quantities in segregated masses, or if present in masses elongated in the direction of forging. The position of the slag in the metal is also of importance, and that which occurs in regions of severest strain is most to be feared. It must always be remembered that in observing slag the particular spot in view is magnified 50 to 100 diameters, and it may be only an isolated spot. If found, an exploration in the neighboring region should be made to see if it is generally distributed. It should also be remembered that low-carbon steels may carry with safety more slag than high-carbon steels. In photographs Nos. 14, 15, 16, 17, 53, 54, and 55 are shown slag areas which would at once arouse suspicion, and if found in ruptured material an exploration would most likely show similar areas throughout the region of fracture.

The inclusion of oxide is frequently accompanied by partial decarbonization, and is most frequently found on or near the surface. An example of this is shown in photograph No. 24, in which it is seen that a crack has penetrated through the slag, probably mill scale, and in the crack are the remnants of the slag. On the left of the crack is the normal structure and on the right is a decarbonized area containing slag. Such an area would probably be large enough to show to the naked eye and would be considered unsafe. Other examples of oxide inclosures are cited on pages 14 and 15, in the discussion of the failure of 10-inch gun and 14-inch gun lever.

STREAKS.

On machining a metal there may often be seen lines or areas on the surface which have a different luster from the main mass of metal, and which frequently machine quite differently from the metal surrounding it; or on polishing and etching, lines of different luster may stand out prominently and invariably elongated in the direction of forging. Such lines or areas are known as streaks or ghost lines, and may occur as either dark or light in comparison to the surrounding metal. Streaks are usually accompanied by slag. If the slag is oxidizing in character, the streak will be decarbonized, and at the same time the ferrite areas will be embrittled by being rich in phosphorus. Such streaks may be the source of fracture, and should be looked upon with suspicion.

Dark-colored streaks usually contain silicate of manganese and are less harmful, the metal showing considerable ductility in the streaked region.

Radial test pieces from gun forgings will frequently show streaks, and as the tension is normal to the direction of extension the specimen will show low ductility. Photographs Nos. 25 and 26 show, respectively, dark and light streaks, and photograph No. 27 shows the microstructure of a portion of the light-colored streak with its decarbonization and accompanying slag. (See also Tests of Metals for 1909, vol. 11.)

HEAT TREATMENT.

It is important that the heat treatment should represent the best practice. This will vary with the purposes for which the material is to be used. In annealed steels the structure should not only show the finest grain which it is possible to give the material but it should be uniform throughout the metal, considering, however, that the mass of metal influences the structure. Thus the surface indications are not always the same as would be found in the center of a large section. Variations between the exterior and interior should therefore be expected on account of slower cooling of the interior and the inability to always have the forging affect the whole mass of metal alike. Coarse structure on the surface will usually indicate coarser material in the center of the mass. Coarse-structured material may pass physical specifications, but nevertheless it does not represent the best practice. Photograph Nos. 28 and 29 represent, respectively, coarse structure and fine structure of the same material, and the latter is undoubtedly the better material, as may be seen from the respective physical properties. Photograph No. 30 shows an undesirably coarse structure, and photograph No. 31 shows a crystalline structure which is not only undesirable but which could have been avoided by suitable heat treatment.

Failure to obtain uniformity of structure is shown in photograph No. 32. Discussion of photographs Nos. 49, 51, and 53 will be found under the discussion of some of the special cases, viz., the failure of 14-inch gun lever arm. Dangerous overheating is shown in photograph No. 33. In this case the material is burnt, as is shown by the oxide between the granules of pearlite.

In material which has been quenched and subsequently tempered there is greater difficulty in defining the structure, but in general it should be fine and usually sorbitic, unless in unusual cases especially high strength and lower ductility is desired, in which cases troostite may be found. In steels in which it is desired to have high strength and high ductility and obtained by either oil or water quenching, followed by a tempering process, and in which the structure is usually sorbitic, it should be

observed that the original martensitic structure is completely removed by the tempering process. This point is illustrated by photograph No. 34 in which there are distinct remains of the original martensitic structure. Such a steel properly heat treated ought to show a structure similar to photographs Nos. 12 or 13.

COMPOSITION.

On slowly cooled or annealed steels the percentage of carbon may be roughly estimated. On quenched steels this estimation is much more difficult and usually impossible. However, with some experience the observer can tell approximately whether or not the percentage of carbon is what the specifications call for. The chemical analysis, however, gives more accurate data and should always be relied upon for final decision. In certain cases, however, a rough microscopic analysis may be made with advantage. For example, in photograph No. 35 (broken recoil spring) there is plainly an excess of cementite, indicating, as was subsequently shown by analysis, about 1.25 per cent of carbon. Such material is evidently unsuited for spring steel on account of the presence of the weak and very brittle constituent, cementite. The main body of this spring showed troostite, not in itself unsuitable, most of the carbon being in solid solution, but the center portion was not cooled rapidly enough to prevent the separation of free cementite. The conclusion is evident that a steel containing less carbon would have been more suitable.

THE EFFECT OF WORK ON GRAIN SIZE.

Steel cooled slowly and undisturbed from a high temperature will show a coarsely granular or crystalline structure, and the size of the grain is a function of the temperature and the time during which the material was held at the maximum temperature, and the rate at which the material was cooled. In large masses of material the structure will be coarser in the center than at the surface, due to the difference in rate of cooling. In order to overcome this difference and at the same time to produce

a homogeneous, uniform material, the steel is work
the period at which grain growth would ordinarily
Steel which has been hot-worked down to the Ar_1 poin
a finer grain, and will be stronger than the same steel slo
without work, and will at the same time show high
Examples of steel worked and unworked are shown
graphs Nos. 28 and 29. Steel which has been wor
Ar_1 — cold-worked — will show considerable distortio
as shown in photograph No. 36.

The following illustrations will serve to indicate typ
ture which have been found in defective material w
in service.

10-INCH RIFLE, MODEL OF 1895.

The tube of this gun was found to be cracked after p
The crack was situated about 2 feet in from the breec
extended in the form of a crescent through a visib
of about 10 inches. At the central portion of the crac
were considerably more separated than at either end
siderable metal had been removed at this point. T
appearance is shown in photograph No. 37. It wil
that the crack is not continuous.

Photographs Nos. 38 and 39 show the macrostruct
steel when etched with iodine, the specimens shown
graph No. 38 being taken longitudinally, radially, a
tially. The segregation of phosphorus is indicated b
lines in pieces Nos. 2 and 5 of photograph No. 38 a
pieces of photograph No. 39 and by the dark spots in
3. Photograph No. 39 shows the metal cut from th
the fracture and treated in the same manner, as sho
piece marked 5 in photograph No. 38, and in other
not shown. The dark streaks were found to be elong
lel to the direction of forging, and it is reasonable
that the elongation will always be parallel to the sur
forged. By inspection of the two larger pieces of meta
the region of the crack (photograph No. 39) it will be
there is considerable distortion of the phosphide area

rifled surface. This would seem to indicate that by some means a fold in the metal had taken place at this point and that in forging it out the phosphide areas had been distorted to the same extent as the surface of the fold.

In photographs of test piece No. 3 is shown a face cut normal to the direction of forging. In all specimens cut in a similar direction there is always the same evidence of ingot structure or primary crystallization, which is indicated by the appearance of the white interpenetrating lines as shown. This crystallization was produced at the time of the passage of the metal from the liquid to the solid state and during the cooling from the temperature of solidification to about 700° C. This is characteristic of ingot crystallization.

Subsequent heat treatment and forging should have completely eliminated all traces of this, and its presence is an indication of faulty manipulation. Further evidence of faulty heat treatment is found in the microstructure of the steel.

Examination of sections in the vicinity of the crack showed many fine cracks, slag inclusions, and carbonless areas. The cracks led to slag, and where the slag was found there were also found decarbonized areas. Photograph No. 40 shows a crack ending in slag and surrounded by decarbonized iron. The course of the slag was quite irregular, as shown in photographs Nos. 41 and 42.

That the slag originated and was folded into the metal during the process of forging rather than during the manufacture of the steel is indicated by the fact that it is strongly oxidizing in character. If it had originated at the time of making the steel, and had then burned out some of the carbon, there would still have been plenty of time for more carbon to have diffused back into these areas. It is found here, however, surrounded by free ferrite along the slag lines, as shown in photograph No. 43 and in photograph No. 44, in which is shown an isolated slag spot surrounded by free ferrite, and this in turn by the normal structure.

Examination was made of the surfaces normal to the lands and grooves of the rifling, and there was no evidence of hardening

of the surface. It is thus highly improbable that a crack could have originated from the presence of hardened metal.

It is believed that the crack in this gun was caused by folding in of some of the metal during forging. Incidentally some other defects are pointed out.

14-INCH GUN LEVER.

This lever was made of cast steel and was broken during the test of the carriage. A microscopic examination revealed the structures shown in photographs Nos. 46 to 51, inclusive.

Photograph No. 46 shows a large amount of segregated ferrite with included slag. These ferrite areas are of such a size that they are easily visible to the eye.

In the fractured ends of the test pieces the metal shows decidedly bright spots, and these are due, it is believed, to the presence of the segregated ferrite. Further, it has been noticed that along the stem of the test pieces incipient cracks are developed, as shown in photograph No. 45. It is highly probable that these incipient fractures are developed in such areas as shown in photograph No. 47, which shows a large ferrite field at the edge of the specimen. It is possible that if the forces are transmitted equally throughout the test piece that such a portion would yield more readily where the carbon was lowest. The strength of such a spot would be approximately that of pure iron, or about 40,000 pounds per square inch, while the darker areas which contain more carbon would show considerably higher values. The presence of much slag in the ferrite areas would also increase the brittleness at this point, and would account for the low ductility in some specimens. Further examples of this form of segregation are shown in photographs Nos. 48 and 49.

The metal has not been annealed in such a way as to remove the original crystallization which took place at the time of solidification. The crystalline structure is shown in photographs Nos. 50 and 51. Proper annealing should have completely wiped out all appearance of this kind. Evidence of this crystalline nature was found in all specimens examined, and it is highly

probable that wherever such structure appears casting strains exist. Proper annealing would also have removed all initial strains and would have refined the structure.

The strength and ductility have undoubtedly been affected by the aforementioned factors, viz., segregated ferrite, crystalline structure, and abundance of slag.

12-INCH NAVY GUN.

A section of the metal 1 inch square was cut from the region of the fracture, and the macrostructure was developed by etching with iodine solution. Photograph No. 52 shows the macrostructure in which is shown several streaks running parallel to the direction of forging on the left-hand face, and on the right-hand face an irregular area of segregation normal to this surface. Small fissures were visible and both faces indicated the presence of slag. Photograph No. 53 shows the microstructure on the longitudinal face in which is seen slag and small fissures. Photographs Nos. 54 and 55 show an unetched and etched area in the longitudinal face, some of the same slag areas being shown in each, and the lack of homogeneity of the metal is evident.

The cause of rupture is believed to have been due to the presence of a zone of streaked metal, and further, that this resulted from the presence of slag in the original ingot.

POLISHING.

To prepare a specimen for microscopic examination it is necessary to polish the surface until a perfectly smooth finish free from scratches is obtained. Frequent examination under the microscope will enable the operator to determine when the polishing should end. Small specimens are easiest to handle, and the threaded ends of broken test specimens are commonly used.

The broken ends are cut off with a saw and smoothed with a dead smooth file, then rubbed on a piece of No. 120 emery cloth and later on a piece of No. 00, care being taken to change direction frequently so that the scratches are at right angles to each other. The piece is then rubbed on a block of wood covered

with felt or canvas and moistened with a preparation of flour of emery and water. This is usually applied with a fine 2-inch brush.

The specimen is then rubbed successively on similar blocks moistened with tripoli and jeweler's rouge. The piece should be carefully cleaned before changing from one abrasive to another.

If power is available it will be found much easier to polish the specimens on rapidly revolving wheels covered with fine duck or broadcloth, to which the abrasive is applied with a brush or in the form of a spray.

After polishing, the specimen is washed carefully in running water and immediately wiped dry with a towel or piece of absorbent cotton.

ETCHING.

An alcoholic solution of nitric acid is the most common reagent used for etching, and is prepared by adding 4 cubic centimeters of nitric acid Sp. Gr. 1.42 to 96 cubic centimeters of grain alcohol.

A small quantity of the acid solution is placed in a porcelain dish, and the polished surface of the prepared specimen immersed for about 10 seconds, the specimen being agitated to prevent adhesion of gas to the surface. It is then removed and washed thoroughly in running water or in alcohol and quickly dried, either by a soft cloth or by a blast of air. Examination under the microscope will determine whether the etching has been carried far enough. The time of etching will vary, depending on the hardness of the steel, and therefore the period must be learned by experience.

A 5 per cent alcoholic solution of picric acid is sometimes used for a reagent, and on low-carbon soft steels it gives practically the same indications as the alcoholic nitric acid. Its use on hardened or tempered steels is not recommended.

Sodium picrate is used to distinguish between ferrite and cementite. This solution is made by dissolving 2 grams of picric acid in 98 cubic centimeters of a solution of 250 grams of caustic

soda (NaOH) dissolved in 750 cubic centimeters of water. The polished specimen is immersed in the boiling solution for 5 to 10 minutes, when the cementite, if present, assumes a blackish coloration. Ferrite remains bright when boiled in sodium picrate solution.

If a permanent record is desired, photomicrographs are made, the magnification being always marked on the negative and print. It will be found that polished surfaces will oxidize if exposed to the air or to moisture. Specimens should be washed in alcohol and stored in air-tight boxes.

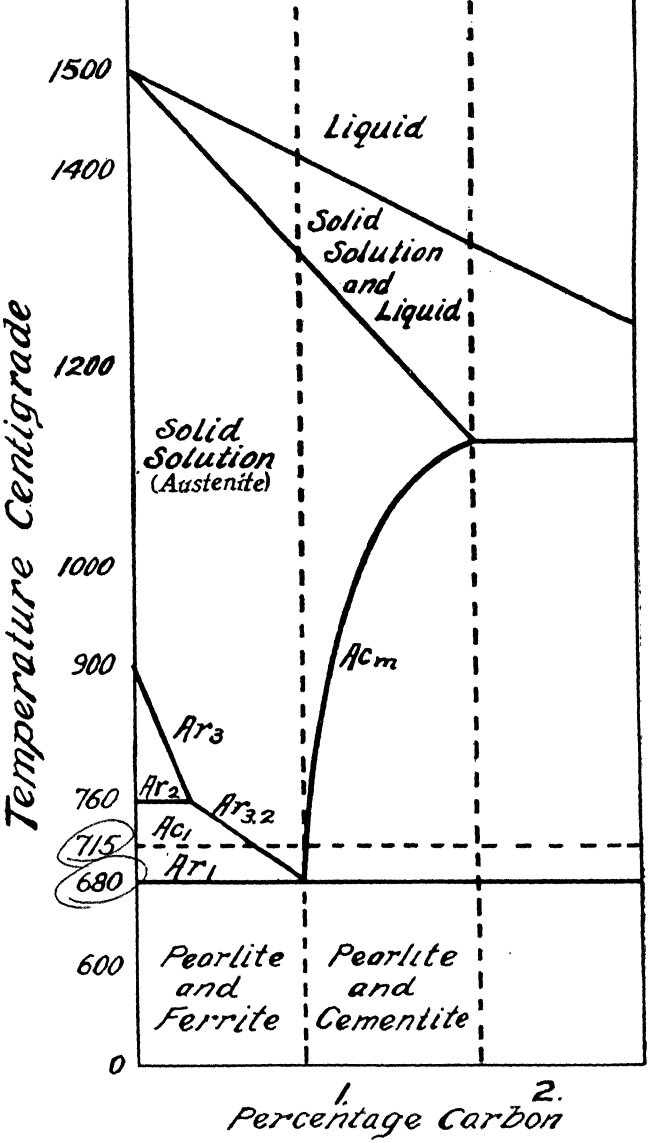
For the examination of large pieces of metal, such as guns, etc., it will be sufficient to polish spots about the size of a 50-cent piece. This can be done with any of the portable outfits now on the market, or may be done by hand.

The study of the following books is recommended, to supplement the information contained herein:

Howe, Metallography of Cast Iron and Steel.
Rosenhain, Physical Metallurgy.
Gulliver, Metallic Alloys.
Edwards, Physico-Chemical Properties of Steel.
Desch, Metallography.
Osmond and Stead, Microscopic Analysis of Metals.

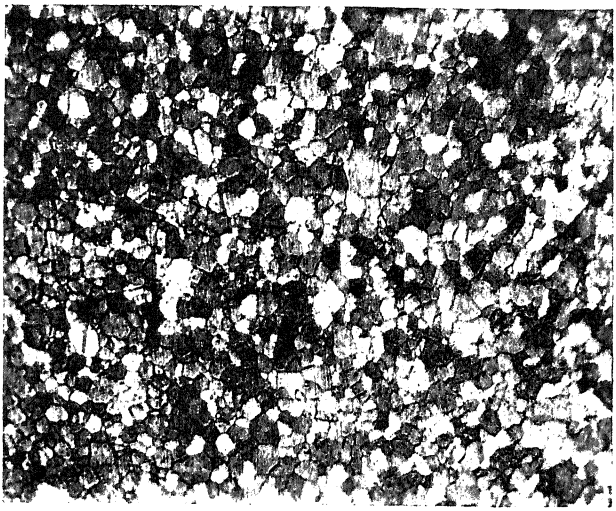
In conclusion it may be stated that there is a tendency to over-rate the application of metallography. Used in connection with the physical tests and chemical analyses it furnishes valuable supplementary data. The inspector is warned to be conservative in his conclusions, at least until he has acquired sufficient experience in the examination of steels to make his conclusions agree with the facts.

It will be found that by the examination of specimens whose heat treatment is definitely known, the inspector will soon acquire a fund of valuable information which will enable him to diagnose an unknown steel correctly. Defective metal should be examined and its characteristics noted whenever and wherever it is found.



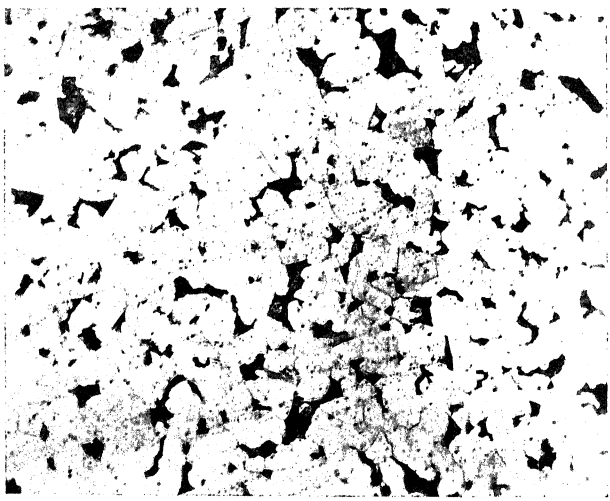
Portion of iron-carbon diagram

Fig. 1



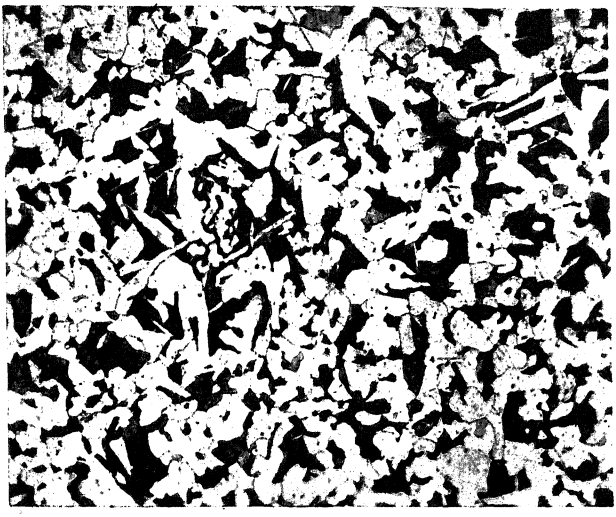
PHOTOGRAPH NO. 1. X75.

0.06% carbon. Approximately pure ferrite.



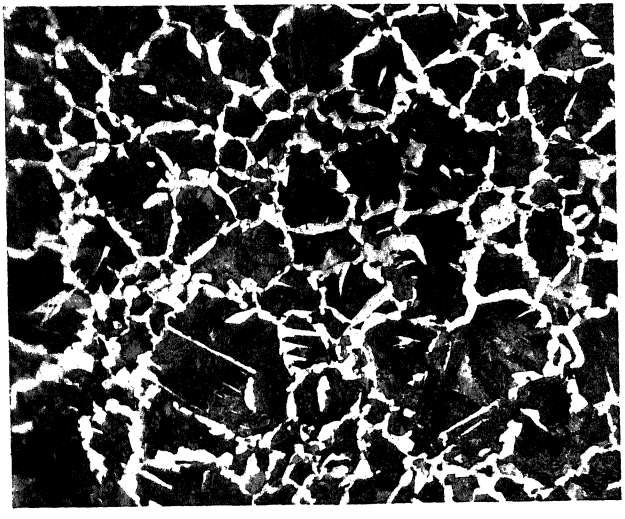
PHOTOGRAPH NO. 2. X75.

0.18% carbon. Ferrite (white) and pearlite (dark).



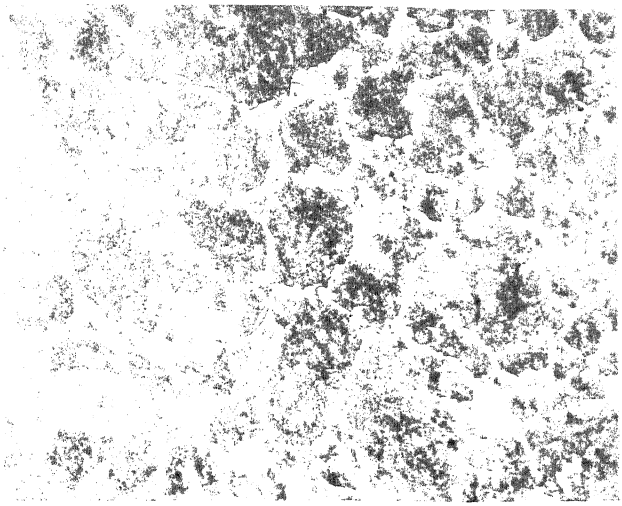
PHOTOGRAPH NO. 3. X75.

0.32% carbon. Ferrite (white) and pearlite (dark).



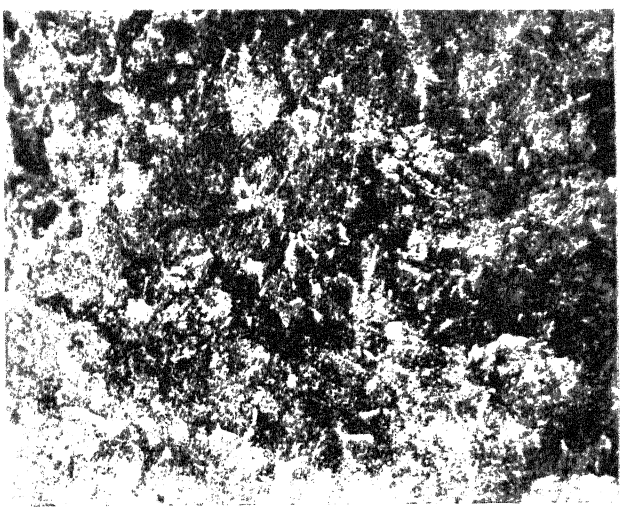
PHOTOGRAPH NO. 4. X75.

0.49% carbon. Ferrite (white) and pearlite (dark).



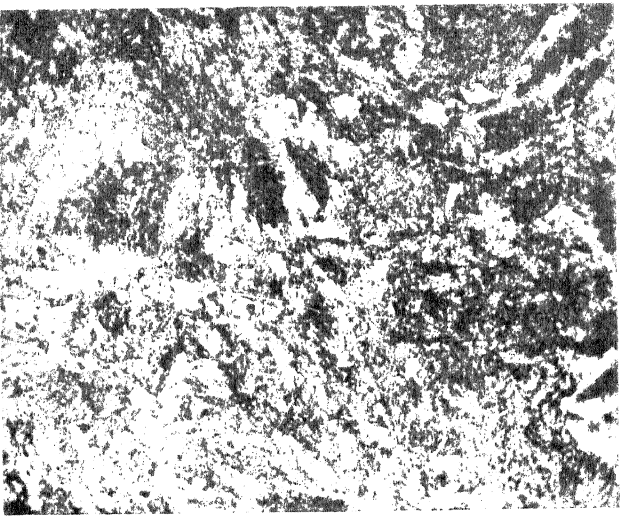
PHOTOGRAPH NO. 5. X75.

0.57% carbon. Ferrite and pearlite.



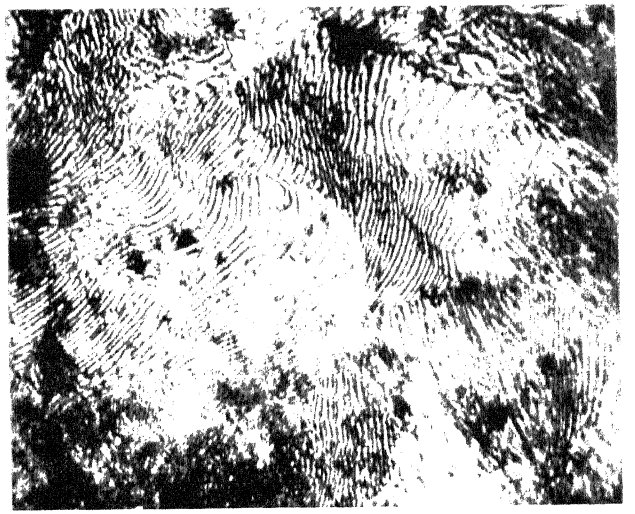
PHOTOGRAPH NO. 6. X75.

0.71% carbon. Ferrite and pearlite.



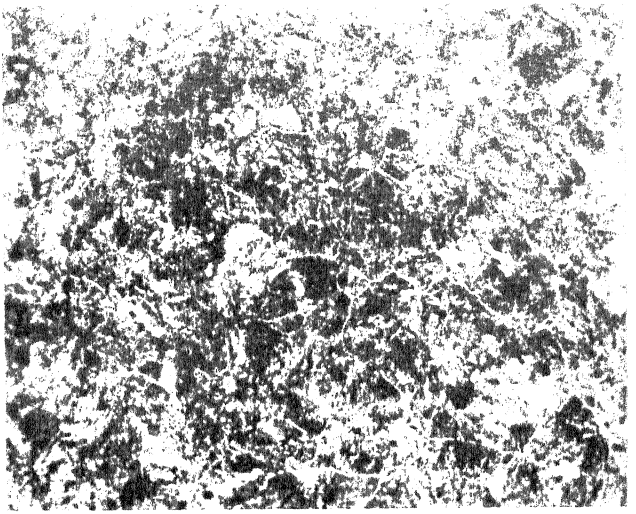
PHOTOGRAPH NO. 7. X75.

0.83% carbon. Pearlite.



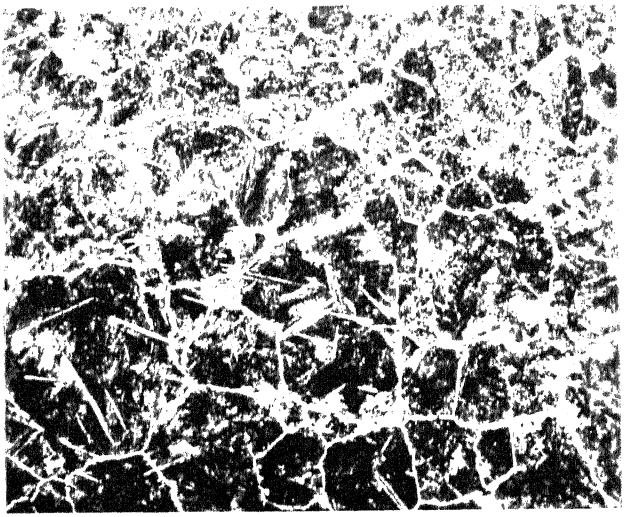
PHOTOGRAPH NO. 8. X485.

0.83% carbon. Pearlite.



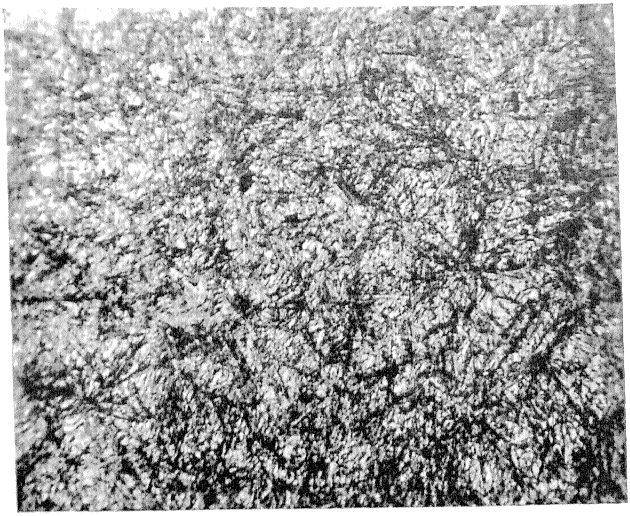
PHOTOGRAPH NO. 9. X75.

1.22% carbon. Pearlite and cementite (white).



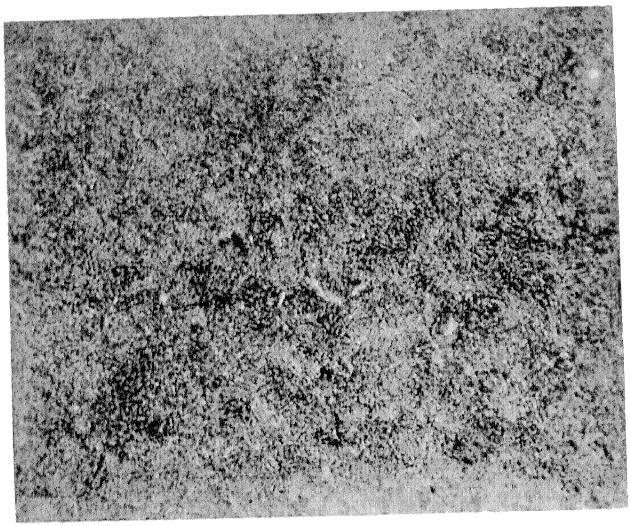
PHOTOGRAPH NO. 10. X75.

1.46% carbon. Pearlite and cementite (white).



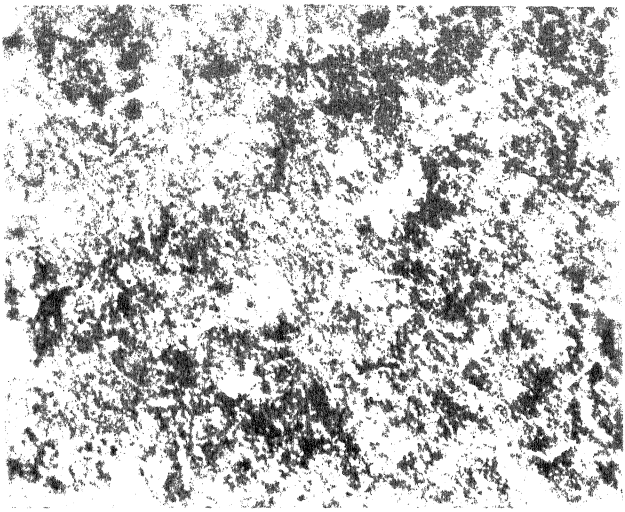
PHOTOGRAPH NO. 11. X75.

Martensite.



PHOTOGRAPH NO. 12. X75.

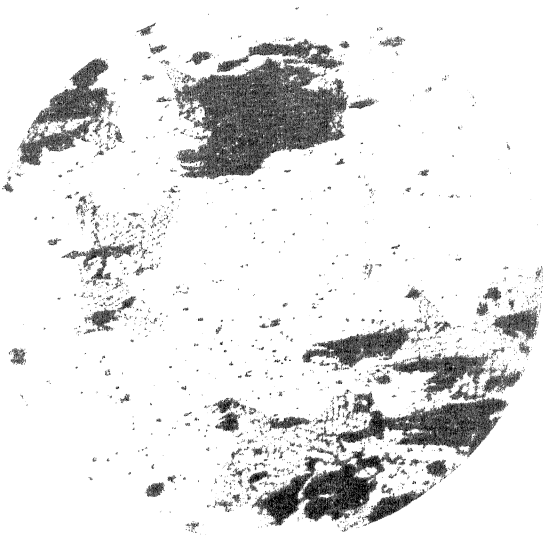
Troostite.



PHOTOGRAPH NO. 13. X75.

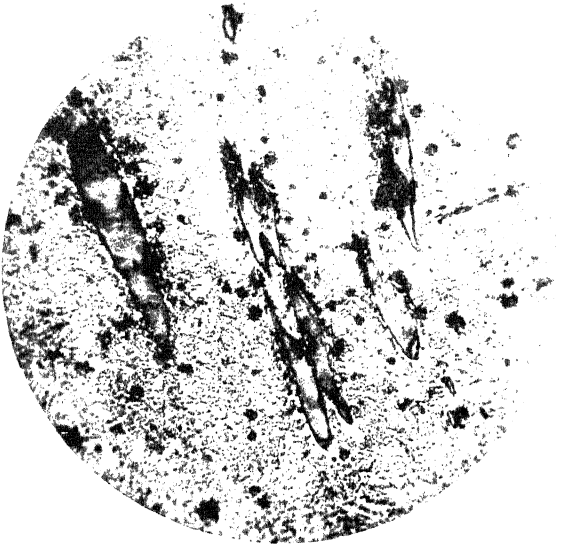
Sorbite.

PHOTOGRAPH NO. 14. X50.



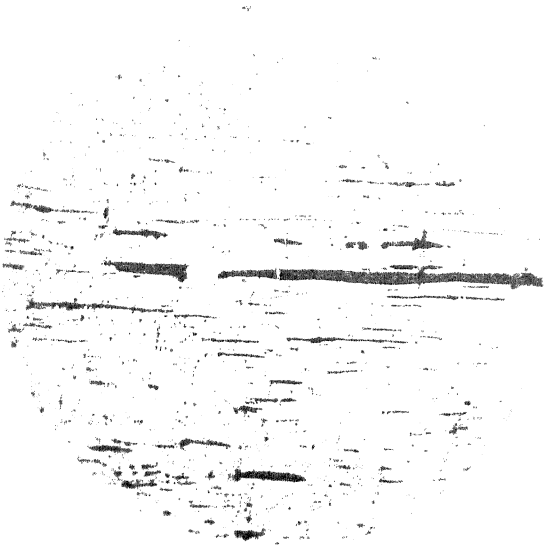
PHOTOGRAPH NO. 15. X50.

Etch figures in silicate of manganese, and cavities due to removal of silicate.



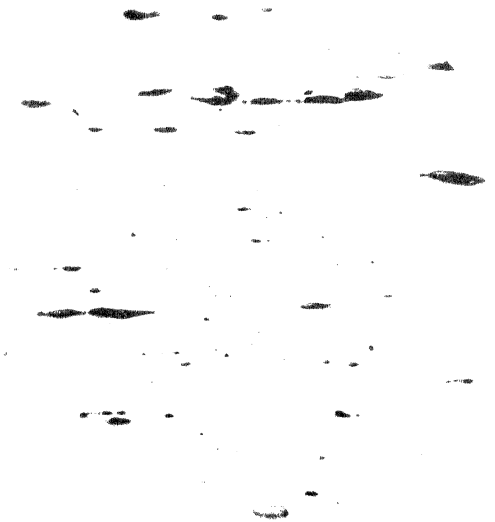
PHOTOGRAPH NO. 16. X50.

Sulphide of manganese in gun steel.



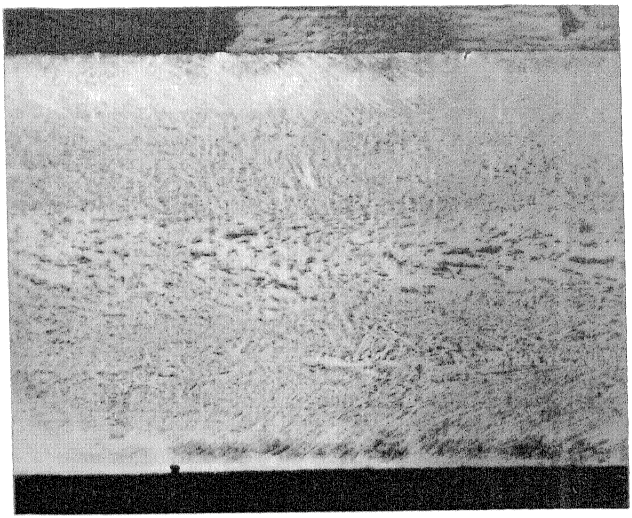
PHOTOGRAPH NO. 17. X50.

Slag elongated in direction of forging. Specimen unetched.

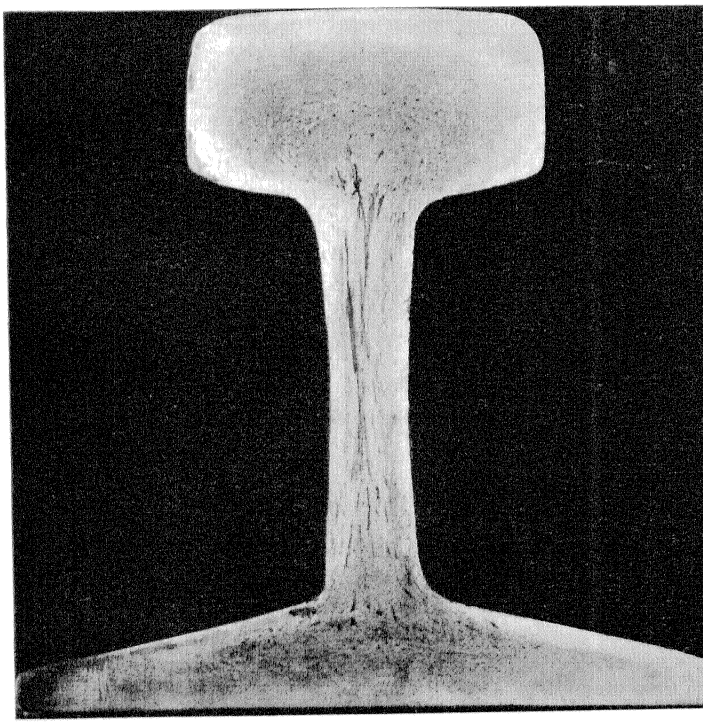


PHOTOGRAPH NO. 18. X50.

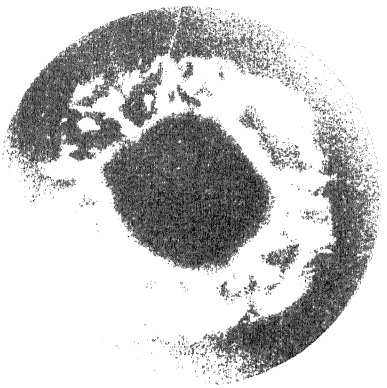
Unevenly distributed slag. Specimen unetched.



PHOTOGRAPH NO. 19. ONE-THIRD SIZE.
Ingot structure in steel.

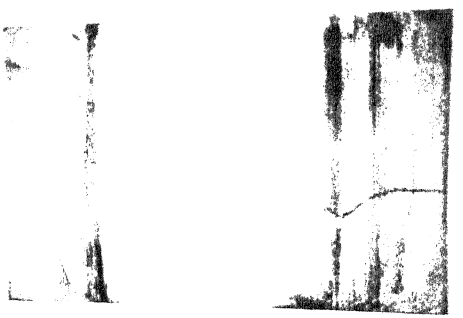


PHOTOGRAPH NO. 20.
Cross section of steel rail showing segregation in center of head, web, and b



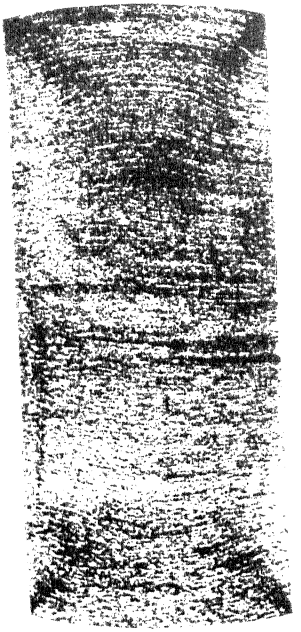
PHOTOGRAPH NO. 21.

Segregation of phosphorus in cold-rolled shafting. Etched with iodine. (White areas.)



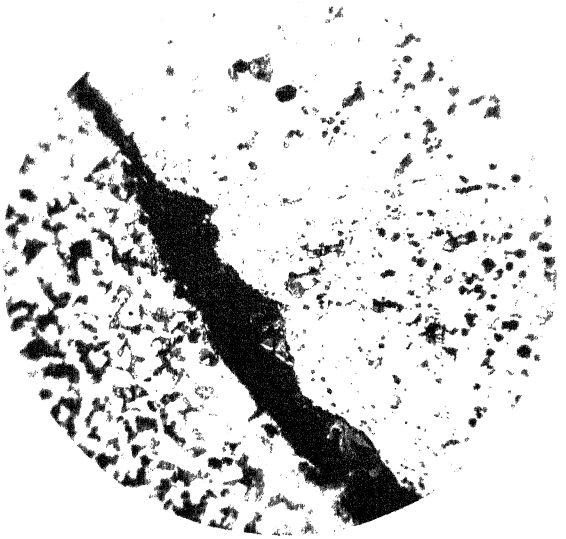
PHOTOGRAPH NO. 22.

Cross section of No. 21. Etched with nitric acid. Dark streaks.)



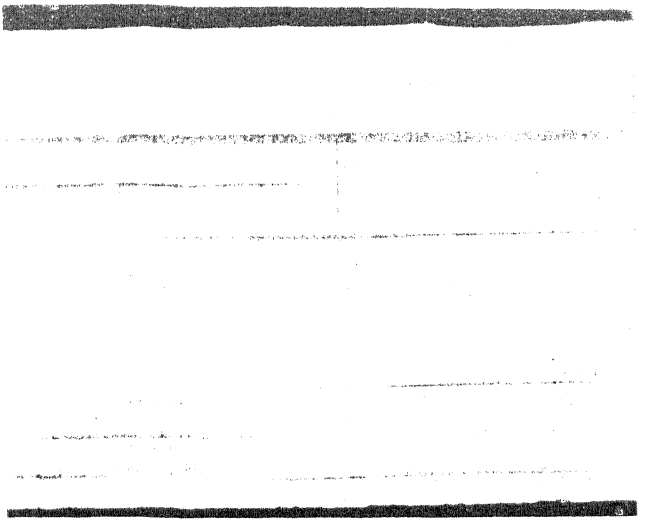
PHOTOGRAPH NO. 23.

Area of strained metal brought out by etching with copper ammonium chloride.



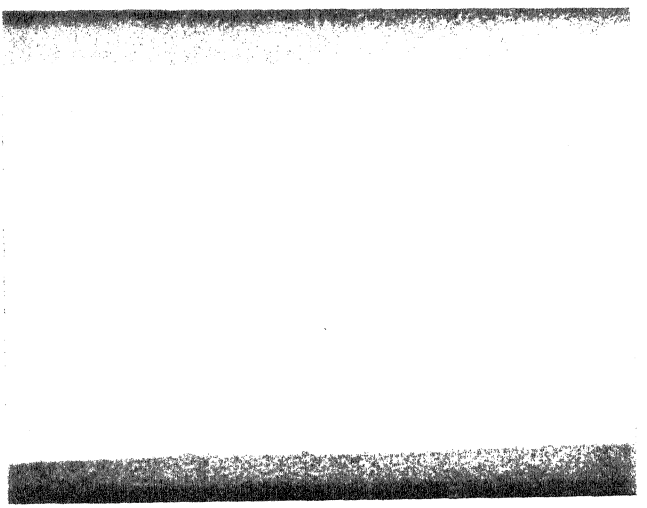
PHOTOGRAPH NO. 24. X50.

Crack, slag, and decarbonized area found on the base of a steel rail.



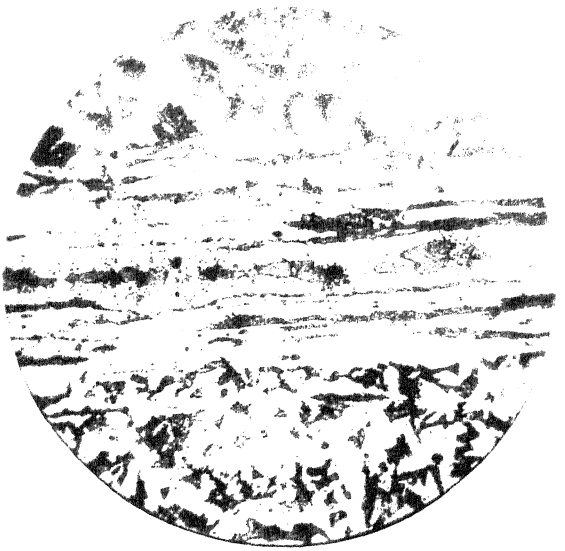
PHOTOGRAPH NO. 25.

Dark streaks in steel rail.



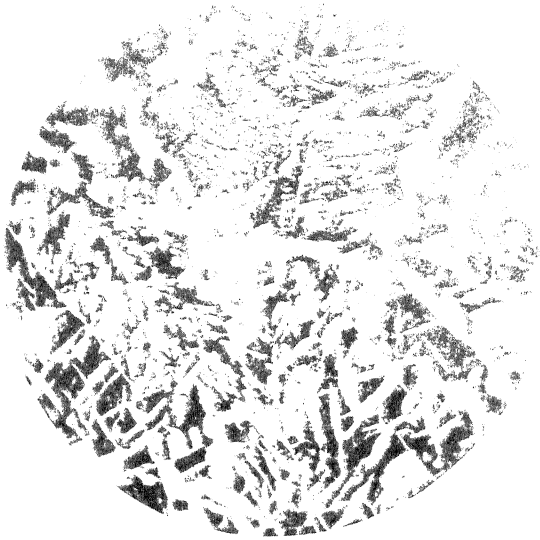
PHOTOGRAPH NO. 26.

Light streaks in steel rail.



PHOTOGRAPH NO. 27. X50.

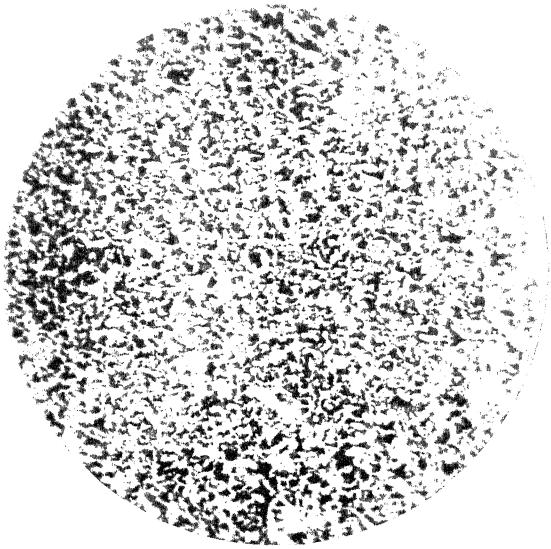
Microstructure of light-colored streak in No. 26.



PHOTOGRAPH NO. 28. X75.

Microstructure of cast steel ingot as cast.

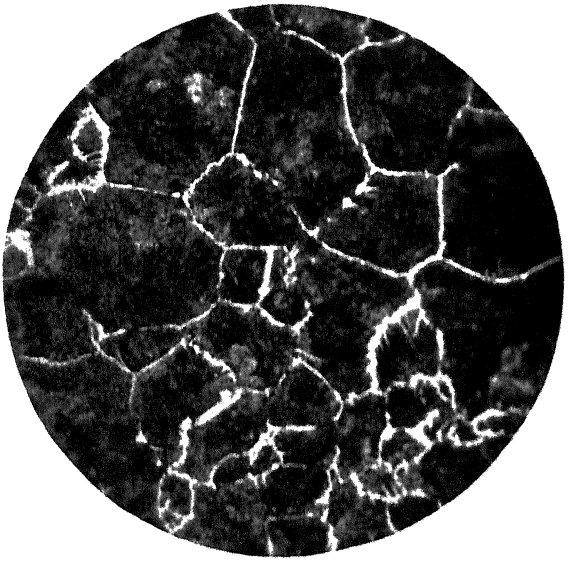
Elastic Limit	39,000
Tensile Strength	77,000
Elongation	10.5
Contraction of Area	16.9



PHOTOGRAPH NO. 29. X75.

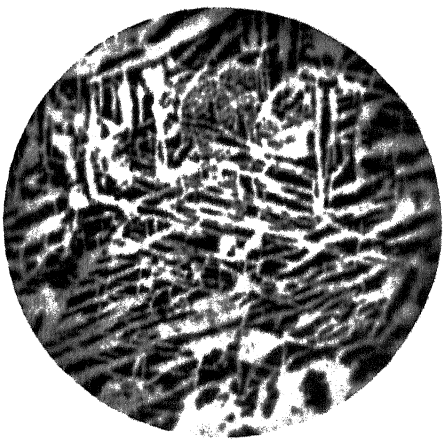
Microstructure of cast steel ingot forged to 1450° F. (788° C.)

Elastic Limit	50,500
Tensile Strength	83,800
Elongation	27.5



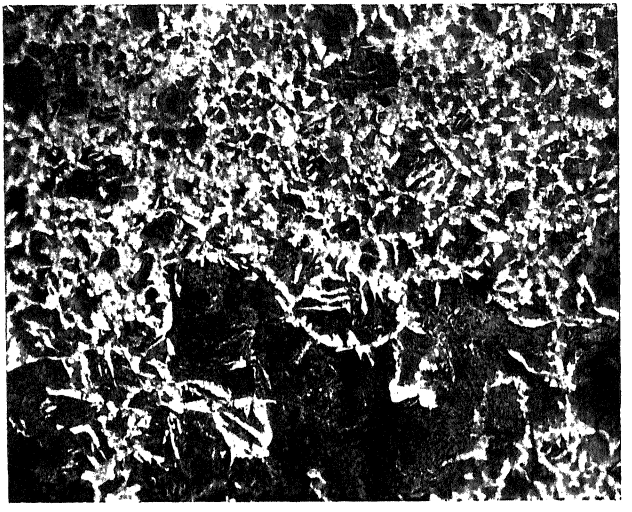
PHOTOGRAPH NO. 30. X75.

Coarse microstructure in gun steel.



PHOTOGRAPH NO. 31. X50.

Crystalline structure in cast steel.

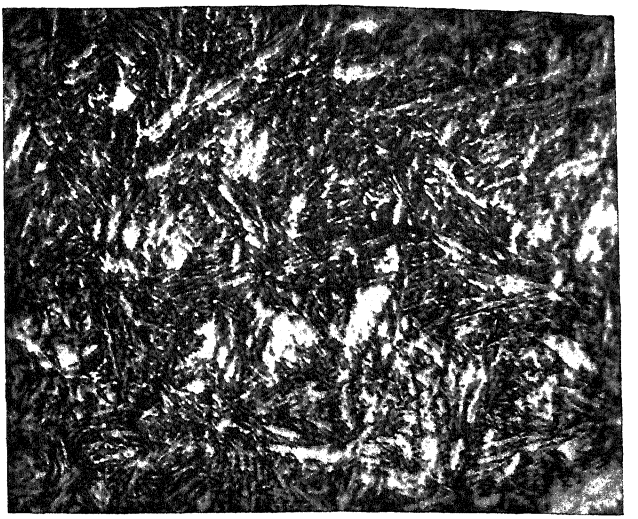


PHOTOGRAPH NO. 32. X75.

Microstructure showing incomplete heat treatment.

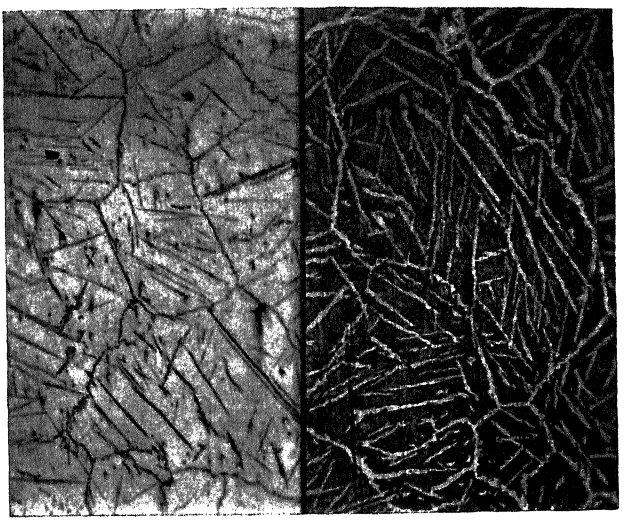
PHOTOGRAPH NO. 33. X75.

Microstructure of overheated steel.



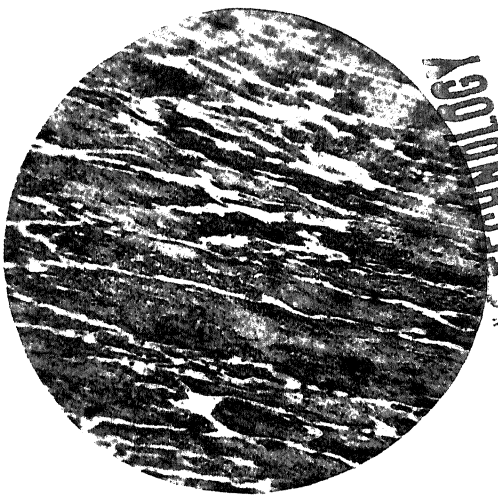
PHOTOGRAPH NO. 34. X500.

Microstructure of forging which had been originally martensitic, and in tempering this structure has not been completely eliminated.



PHOTOGRAPH NO. 35. X65.

Microstructure in center of broken recoil spring showing excess cementite, indicating high carbon. Left, white lines are cementite etched with nitric acid solution; right, dark lines are cementite etched with sodium picrate solution.



PHOTOGRAPH NO. 36. X50.

Microstructure of steel subjected to cold work, and showing distortion of grain.

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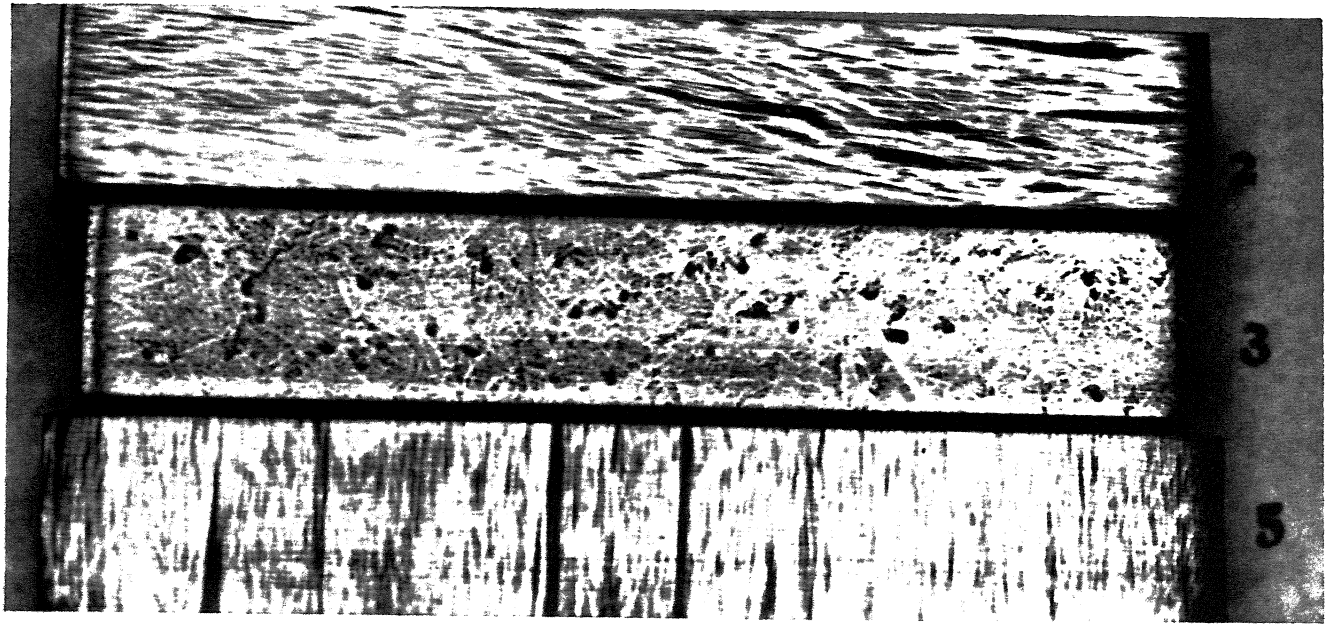
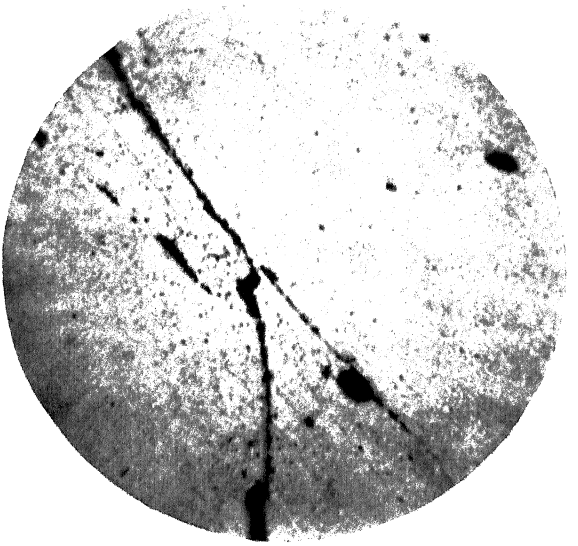


PHOTOGRAPH NO. 38.

Macrostructure of test bars of 10-inch pipe showing surfaces cut longitudinal 5, radial 3, and tangential 2 to axis.

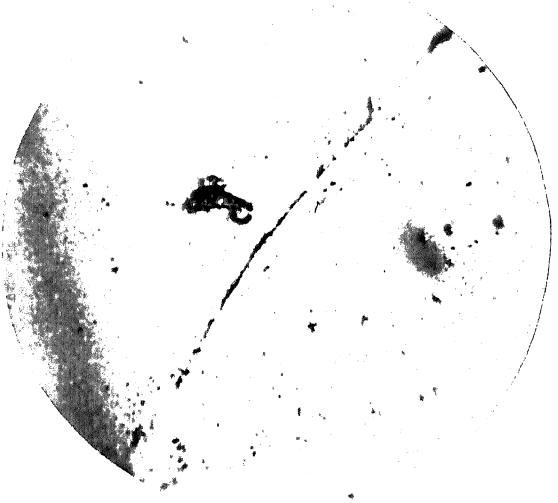
PHOTOGRAPH NO. 40. X50.

Crack and slag, with decarbonized area in 10-inch rifle.



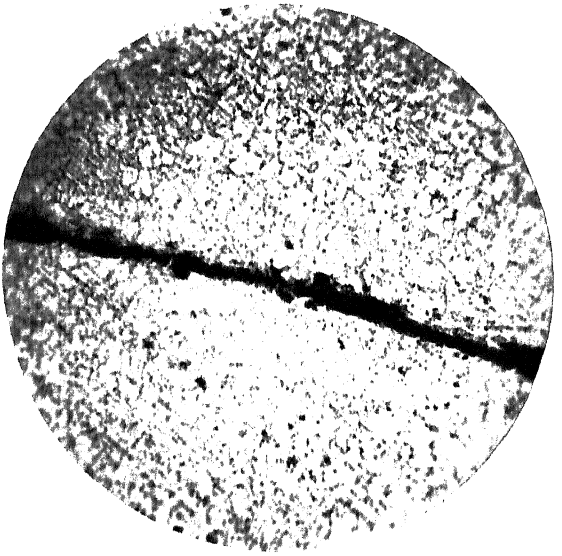
PHOTOGRAPH NO. 41. X50.

Slag in 10-inch rifle, unetched.



PHOTOGRAPH NO. 42. X50.

Slag in 10-inch rifle, unetched.

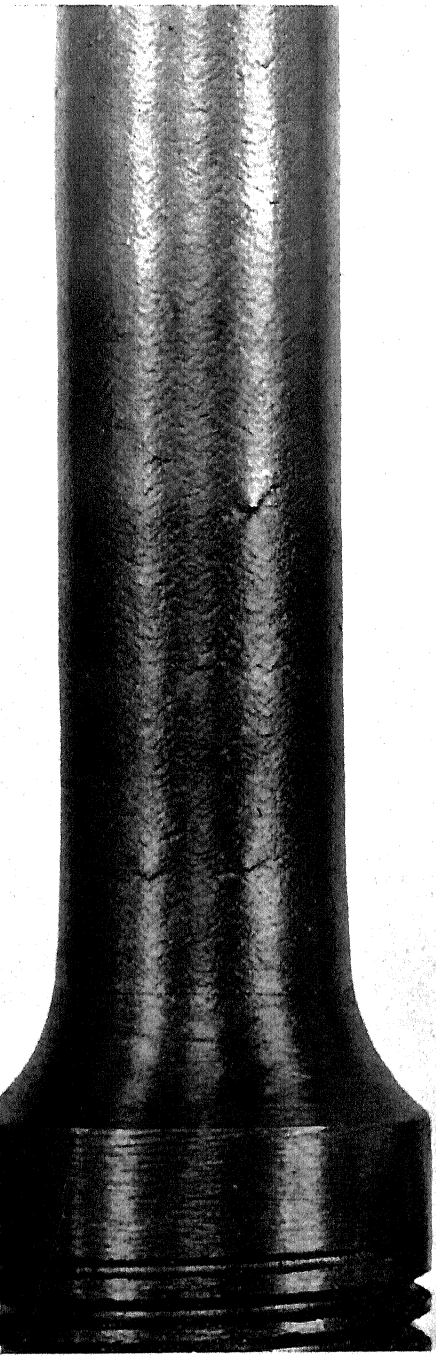


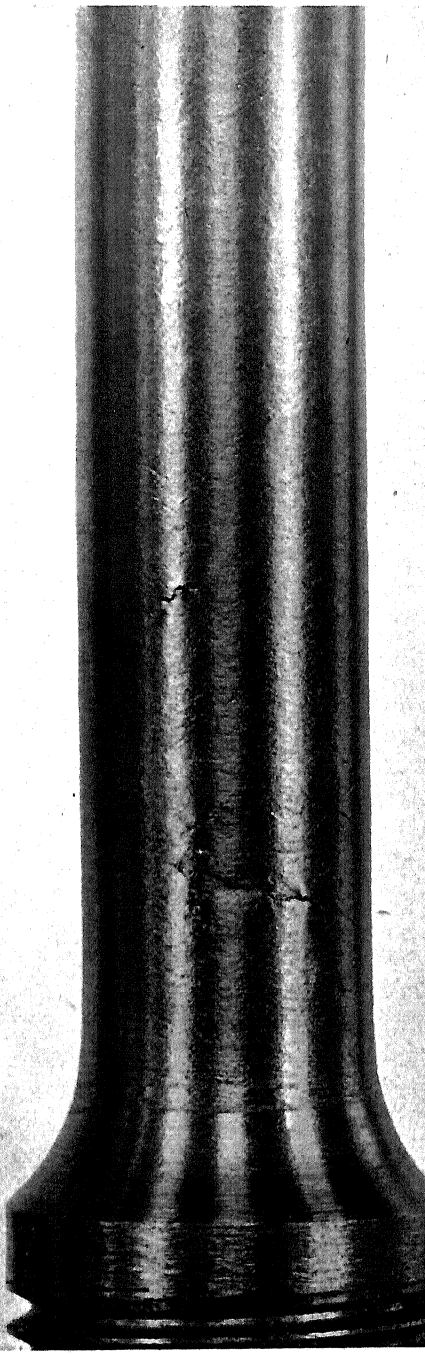
PHOTOGRAPH NO. 43. X50.

Slag and decarbonized area in 10-inch rifle.

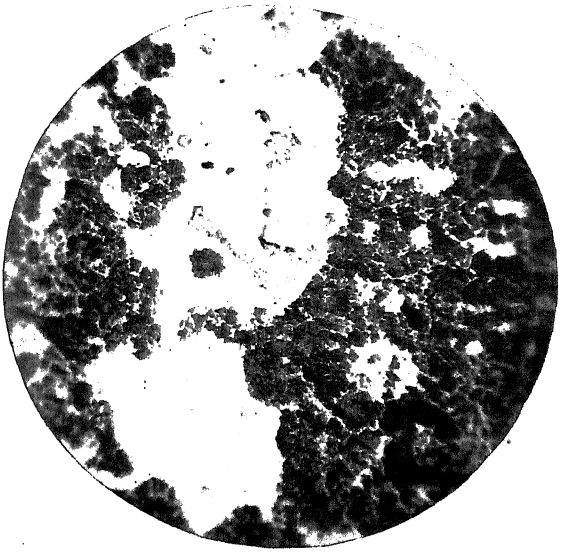
PHOTOGRAPH NO. 44. X50.

Island of slag in decarbonized area in 10-inch rifle.





OIB. A1.

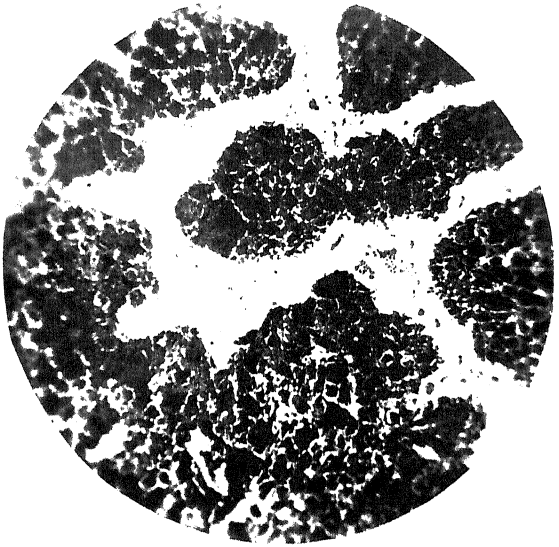


PHOTOGRAPH NO. 46. X50.

Fourteen-inch gun lever. Segregated ferrite (white) with slag inclosures.

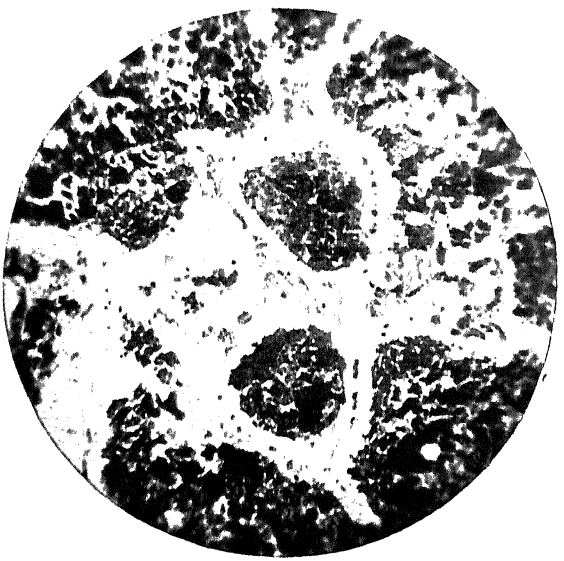
PHOTOGRAPH NO. 47. X50.

Fourteen-inch gun lever. Segregated ferrite on edge of test piece. Slag inclusions.



PHOTOGRAPH NO. 48. X50.

Fourteen-inch gun lever. Segregated ferrite (white) with slag inclusions.



PHOTOGRAPH NO. 49. X50.

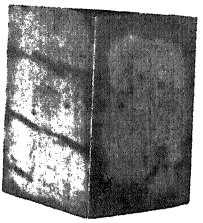
Fourteen-inch gun lever. Segregated ferrite with slag inclusions.

PHOTOGRAPH NO. 50. X50.

Fourteen-inch gun lever. Segregated ferrite and crystalline structure.

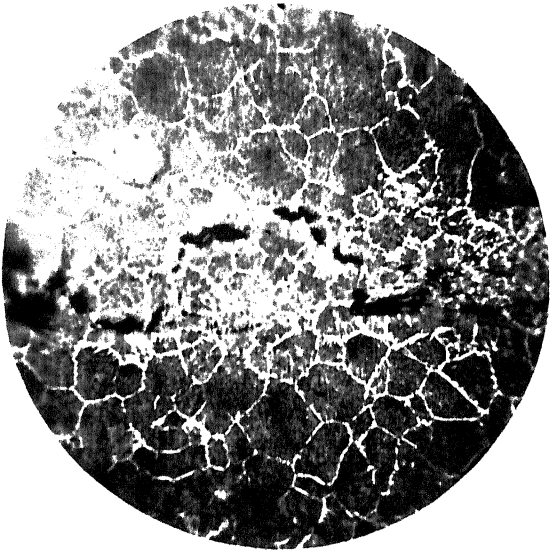
PHOTOGRAPH NO. 51. X50.

Fourteen-inch gun lever. Crystalline structure.



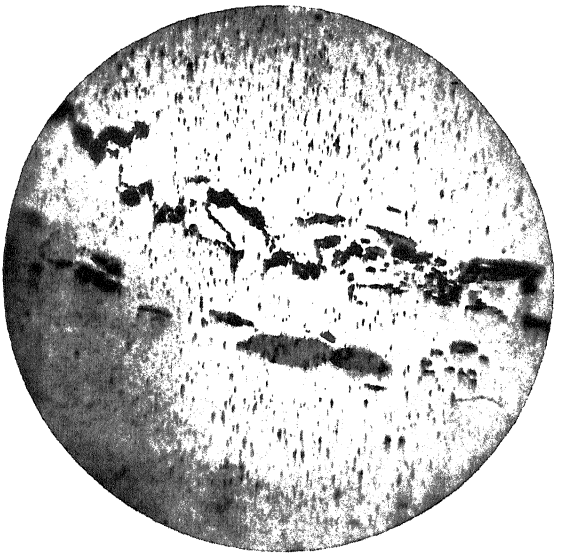
PHOTOGRAPH NO. 52.

Macrostructure of metal removed from 12-inch gun.



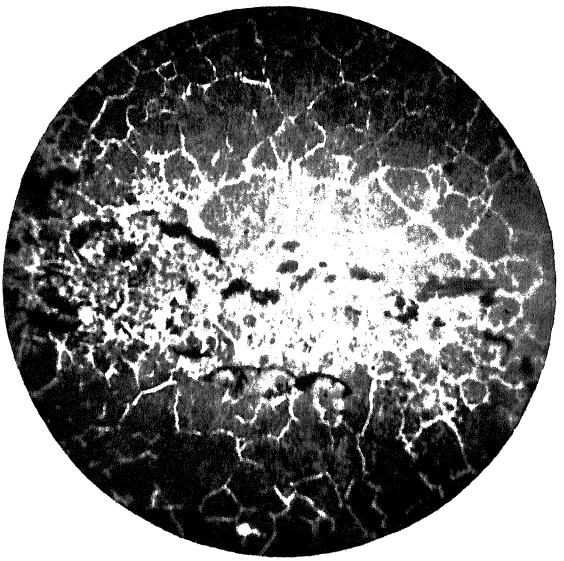
PHOTOGRAPH NO. 53. X50.

Twelve-inch gun. Microstructure showing slag and fissures.



PHOTOGRAPH NO. 54. X50.

Twelve-inch gun. Slag in unetched specimen.



PHOTOGRAPH NO. 55. X50.

Twelve-inch gun. Same area as No. 54, etched with alcoholic nitric acid.